

INTRODUCTION

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Abstract

It is embarrassing that 95% of the universe is unaccounted for. Galaxies and larger-scale cosmic structures are composed mainly of ‘dark matter’ whose nature is still unknown. Favoured candidates are weakly-interacting particles that have survived from the very early universe, but more exotic options cannot be excluded. (There are strong arguments that the dark matter is not composed of baryons). Intensive experimental searches are being made for the ‘dark’ particles (which pervade our entire galaxy), but we have indirect clues to their nature too. Inferences from galactic dynamics and gravitational lensing allow astronomers to ‘map’ the dark matter distribution; comparison with numerical simulations of galaxy formation can constrain (eg) the particle velocities and collision cross sections. And, of course, progress in understanding the extreme physics of the ultra-early universe could offer clues to what particle might have existed then, and how many would have survived.

The mean cosmic density of dark matter (plus baryons) is now pinned down to be only about 30% of the so-called critical density corresponding to a ‘flat’ universe. However, other recent evidence – microwave background anisotropies, complemented by data on distant supernovae – reveals that our universe actually is ‘flat’, but that its dominant ingredient (about 70% of the total mass-energy) is something quite unexpected — ‘dark energy’ pervading all space, with negative pressure. We now confront two mysteries:

- (i) Why does the universe have three quite distinct basic ingredients – baryons, dark matter and dark energy – in the proportions (roughly) 5%, 25% and 70%?
- (ii) What are the (almost certainly profound) implications of the ‘dark energy’ for fundamental physics?

1 SOME HISTORY

Astronomers have long known that galaxies and clusters would fly apart unless they were held together by the gravitational pull of much more material than we actually see.

The strength of the case built up gradually. The argument that clusters of galaxies would be unbound without dark matter dates back to Zwicky (1937) and others in the 1930s. Kahn and Woltjer (1959) pointed out that the motion of Andromeda towards us implied that there must be dark matter in our Local

Group of galaxies. But the dynamical evidence for massive halos (or ‘coronae’) around individual galaxies firmed up rather later (e.g. Roberts and Rots 1973, Rubin, Thonnard and Ford 1978).

Two 1974 papers were specially influential in the latter context. Here is a quote from each:

The mass of galactic coronas exceeds the mass of populations of known stars by one order of magnitude, as do the effective dimensions. The mass/luminosity ratio rises to $f=100$ for spiral and $f = 120$ for elliptical galaxies. With $H = 50$ km/sec/Mpc this ratio for the Coma cluster is 170 (Einasto, Kaasik and Saar 1974)

Currently-available observations strongly indicate that the mass of spiral galaxies increases almost linearly with radius to nearly 1 Mpc.... and that the ratio of this mass to the light within the Holmberg radii, f , is 200 (M/L_{\odot}). (Ostriker, Peebles and Yahil, 1974).

The amount of dark matter, and how it is distributed, is now far better established than it was when those papers were written. The immense advances in delineated dark matter in clusters and in individual galaxies are manifest in the programme for this meeting. The rapid current progress stems from the confluence of several new kinds of data within the same few-year interval: optical surveys of large areas and high redshifts, CMB fluctuation measurements, sharp X-ray images, and so forth.

The progress has not been solely observational. Over the last 20 years, a compelling theoretical perspective for the emergence of cosmic structure has been developed. The expanding universe is unstable to the growth of structure, in the sense that regions that start off *very slightly* overdense have their expansion slowed by their excess gravity, and evolve into conspicuous density contrasts. According to this ‘cold dark matter’ (CDM) model, the present-day structure of galaxies and clusters is moulded by the gravitational aggregation of non-baryonic matter, which is an essential ingredient of the early universe (Pagels and Primack 1982, Peebles 1982, Blumenthal *et al.* 1984, Davis *et al.* 1985). These models have been firmed up by vastly improved simulations, rendered possible by burgeoning computer power. And astronomers can now compare these ‘virtual universes’ with the real one, not just at the present era but (by observing very distant objects) can probe back towards the formative stages when the first galaxies emerged.

The following comments are intended to provide a context for the later papers. (For that reason, I do not give detailed references to the topics covered by other speakers – just some citations of historical interest).

2 THE CASE FOR DARK MATTER

2.1 Baryons

The inventory of cosmic baryons is readily compiled. Stars and their remnants, and gas in galaxies, contribute no more than 1% of the critical density (i.e. they give $\Omega_b < 0.01$). However several percent more could be contributed by diffuse material pervading intergalactic space: warm gas (with $kT \simeq 0.1$ keV) in groups of galaxies and loose clusters, and cooler gas pervading intergalactic space that manifests itself via the ‘picket fence’ absorption lines in quasar spectra. (Rich clusters are rare, so their conspicuous gas content, at several KeV, is not directly significant for the total inventory, despite its importance as a probe)

These baryon estimates are concordant with those inferred by matching the He and D abundances at the birth of galaxies with the predicted outcome of nucleosynthesis in the big bang, which is sensitive to the primordial baryon/photon ratio, and thus to Ω_b . The observational estimates have firmed up, with improved measurements of deuterium in high- z absorbing clouds. The best fit occurs for $\Omega_b \simeq 0.02h^{-2}$ where h is the Hubble constant in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Observations favour $h \simeq 0.7$.

Ω_b is now pinned down by a variety of argument to be $0.04 - 0.05$. This corresponds to only ~ 0.3 baryons per cubic metre, a value so low that it leaves little scope for dark baryons. (It is therefore unsurprising that the MACHO/OGLE searches should have found that compact objects do not make a substantial contribution to the total mass of our own galactic halo.)

2.2 How much dark matter?

An important recent development is that Ω_{DM} can now be constrained to a value around 0.25 by several independent lines of evidence:

(i) One of the most ingenious and convincing arguments comes from noting that baryonic matter in clusters – in galaxies, and in intracluster gas – amounts to $0.15 - 0.2$ of the inferred virial mass (White *et al.* 1993). If clusters were a fair sample of the universe, this would then be essentially the same as the cosmic ratio of baryonic to total mass. Such an argument could not be applied to an individual galaxy, because baryons segregate towards the centre. However, there is no such segregation on the much larger scale of clusters: only a small correction is necessary to allow for baryons expelled during the cluster formation process.

(ii) Very distant galaxies appear distorted, owing to gravitational lensing by intervening galaxies and clusters. Detailed modelling of the mass-distributions needed to cause the observed distortions yields a similar estimate. This is a straight measurement of Ω_{DM} which (unlike (i)) does not involve assumptions about Ω_b , though it does depend on having an accurate measure of the clustering amplitude.

(iii) Another argument is based on the way density contrasts grow during the cosmic expansion: in a low density universe, the expansion kinetic energy overwhelms gravity, and the growth of structure saturates at recent epochs. The existence of conspicuous clusters of galaxies with redshifts as large as $z = 1$ is hard to reconcile with the rapid recent growth of structure that would be expected if Ω_{DM} were unity. More generally, numerical simulations based on the cold dark matter (CDM) model are a better fit to the present-day structure for this value of Ω_{DM} (partly because the initial fluctuation spectrum has too little long-wavelength power if Ω_{DM} is unity).

Other methods will soon offer independent estimates. For instance, Ω_{DM} can be estimated from the deviations from the Hubble flow induced by large-scale irregularities in the mass distribution on supercluster scales.

2.3 What could the dark matter be?

The dark matter is not primarily baryonic. The amount of deuterium calculated to emerge from the big bang would be far lower than observed if the average baryon density were ~ 2 (rather than ~ 0.3) per cubic metre. Extra exotic particles that do not participate in nuclear reactions, however, would not scupper the concordance.

Beyond the negative statement that it is non-baryonic, the nature of the dark matter still eludes us. This key question may yield to a three-pronged attack:

1. Direct detection. As described by other contributors to this meeting, several groups are developing cryogenic detectors for supersymmetric particles and axions. This is an exciting quest. Of course, not even optimists can be confident that the actual dark matter particles have parameters within the range that these experiments are yet sensitive to. But the stakes are high: detection of most of the gravitating stuff in the universe, as well as a new class of elementary particle. So it seems well worth committing to these experiments funding that is equivalent to a small fraction of the cost of a major accelerator.
2. Progress in particle physics. Important recent measurements suggest that neutrinos have non-zero masses; this result has crucially important implications for physics beyond the standard model. The inferred neutrino masses seem, how-

ever, too low to be cosmologically important. If the masses and cross-sections of supersymmetric particles were known, it should be possible to predict how many survive, and their contribution to Ω , with the same confidence with which we can compute the nuclear reactions that control primordial nucleosynthesis. Associated with such progress, we might expect a better understanding of how the baryon-antibaryon asymmetry arose, and the consequence for Ω_b . Optimists may hope for progress on still more exotic options.

3. Simulations of galaxy formation and large-scale structure. When and how galaxies form, the way they are clustered, and the density profiles within individual systems, depend on what their gravitationally-dominant constituent is. A combination of better data and better simulations is starting to set generic constraints on the options. The CDM model works well. But there are claimed discrepancies, though many of us suspect these may ease when the galaxy formation process is better understood. For instance the centre of a halo would, according to the simulations, have a ‘cusp’ rather than the measured uniform-density core: this discrepancy has led some authors to explore modifications where the particles are assumed to have significant collision probabilities, or to be moving with non-negligible velocities (i.e. ‘warm’ not cold.). These calculations are in any case offering interesting constraints on the properties of heavy supersymmetric particles. (Also, straight astronomical observations can rule out a contribution to Ω of more than 0.01 from neutrinos – this is compatible with current experimental estimates.)

3 DARK ENERGY

The inference that our universe is dominated by dark matter is in itself a discovery of the first magnitude. But the realisation that even more mass-energy is in some still more mysterious form – dark energy latent in space itself – came as a surprise, and probably has even greater import for fundamental physics.

If this meeting had been taking place 3 years ago, the more open-minded among us would have given equal billing to two options: a hyperbolic universe with Ω of 0.3, (in which it would be a coincidence that the Robertson-Walker curvature radius was comparable with the present Hubble radius), or a flat universe in which something other than CDM makes up the balance, equivalent to Ω of 0.7 (In this case it would be a coincidence that two quite different invisible substances make comparable contributions).

But it is now clear that only the second option remains in the running: there is compelling evidence that the universe is flat. This evidence comes from the slight temperature-differences over the sky in the background radiation, due to density irregularities which are the precursors of cosmic structure. Theory tell

us that the temperature fluctuations should be biggest on a particular length scale that is related to the distance a sound wave can travel in the early universe. The angular scale corresponding to this length depends, however, on the geometry of the universe. If dark matter and baryons were all, we wouldn't be in a flat universe – the geometry would be hyperbolic. Distant objects would look smaller than in a flat universe. In 2001-02, measurements from balloons and from Antarctica pinned down the angular scale of this ‘doppler peak’: the results indicated ‘flatness’ – a result now confirmed with greater precision by the WMAP satellite.

A value of 0.3 for Ω_{DM} would imply (were there no other energy in the universe) an angle smaller by almost a factor of 2 – definitely in conflict with observations. So what's the other 70%? It is not dark matter but something that does not cluster – some energy latent in space. The simplest form of this idea goes back to 1917 when Einstein introduced the cosmological constant, or λ . A positive λ can be interpreted, in the context of the ordinary Friedman equations, as a fixed positive energy density in all space. This leads to a repulsion because, according to Einstein's equation, gravity depends on pressure as well as density, and vacuum energy has such a large negative pressure – tension – that the net effect is repulsive.

Einstein's cosmological constant is just one of the options. A class of more general models is being explored (under names such as ‘quintessence’) where the energy is time-dependent. Any form of dark energy must have negative pressure to be compatible with observations – unclustered relativistic particles, for instance, can be ruled out as candidates. The argument is straightforward: at present, dark energy dominates the universe – it amounts to around 70% of the total mass-energy. But had it been equally dominant in the past, it would have inhibited the growth of the density contrasts in cosmic structures, which occurred gravitational instability. This is because the growth timescale for gravitational instability is $\sim (G\rho_c)^{-\frac{1}{2}}$, where ρ_c is the density of the component that participates in the clustering, whereas the expansion timescale scales as $(G\rho_{total})^{-\frac{1}{2}}$ when curvature is unimportant. If ρ_{total} exceeds ρ_c , the expansion is faster, so the growth is impeded. (Meszaros, 1974)

In the standard model, density contrasts in the dark matter grow by nearly 1000 since recombination. If this growth had been suppressed, the existence of present-day clusters would therefore require irregularities that were already of substantial amplitude at the recombination epoch, contrary to the evidence from CMB fluctuations. For the ‘dark energy’ to be less dominant in the past, its density must depend on the scale factor R more slowly than the R^{-3} dependence of pressure-free matter – i.e. its PdV work must be negative. Cosmologists have introduced a parameter w such that $p = w\rho c^2$. A more detailed treatment yields the requirement that $w < -0.5$. This comes from taking account of baryons and dark matter, and requiring that dark energy should not have inhibited the

growth of structure so much that it destroyed the concordance between the CMB fluctuations (which measure the amplitude at recombination) and the present-day inhomogeneity. Note however that unless its value is -1 (the special case of a classical cosmological constant) w will generally be time-dependent. In principle $w(t)$ can be pinned down by measuring the Hubble expansion rate at different redshifts

This line of argument would in itself have led to a prediction of accelerating cosmic expansion. However, as it turned out, studies of the redshift versus the apparent brightness of distant SNIa – strongly suggestive if not yet completely compelling – had already conditioned us to the belief that galaxies are indeed dispersing at an accelerating rate. As often in science, a clear picture gradually builds up, but the order in which the bits of the jigsaw fall into place is a matter of accident or contingency. CMB fluctuations alone can now pin down Ω_{DM} and the curvature independent of all the other measurements.

The ‘modern’ interest in the cosmological constant stems from its interpretation as a vacuum energy. This leads to the reverse problem: Why is λ at least 120 powers of 10 smaller than its ‘natural’ value, even though the effective vacuum density must have been very high in order to drive inflation. If λ is fully resurrected, it will be a posthumous ‘coup’ for de Sitter. His model, dating from the 1920s, not only describes inflation, but would then also describe future aeons of our cosmos with increasing accuracy. Only for the 50-odd decades of logarithmic time between the end of inflation and the present would it need modification!. But of course the dark energy could have a more complicated and time-dependent nature – though it must have negative pressure, and it must not participate in gravitational clustering.

4 SUMMARY AND PROSPECTS

Cosmologists can now proclaim with confidence (but with some surprise too) that, in round numbers, our universe consists of 5% baryons, 25% dark matter, and 70% dark energy. It is indeed embarrassing that 95% of the universe is unaccounted for: even the dark matter is of quite uncertain nature, and the dark energy is a complete mystery.

The network of key arguments is summarised in Figure 1. Historically, the supernova evidence came first. But had the order of events been different, one could have predicted an acceleration on the basis of CDM evidence alone; the supernovae would then have offered gratifying corroboration (despite the unease about possible poorly-understood evolutionary effects).

Our universe is flat, but with a strange mix of ingredients. Why should these all

give comparable contributions (within a modest factor) when they could have differed by a hundred powers of ten?

In the coming decade, we can expect advances on several fronts. Physicists may well develop clearer ideas on what determined the favouritism for matter over antimatter in the early universe, and on the particles that make up the dark matter. Understanding the dark energy, and indeed the big bang itself, is perhaps a remoter goal, but ten years from now theorists may well have replaced the boisterous variety of ideas on the ultra-early universe by a firmer best buy. They will do this by discovering internal inconsistencies in some contending theories, and thereby narrowing down the field. Better still, maybe one theory will earn credibility by explaining things we can observe, so that we can apply it confidently even to things we cannot directly observe. In consequence, we may have a better insight into the origin of the fluctuations, the dark energy, and perhaps the big bang itself.

Inflation models have two generic expectations; that the universe should be flat and that the fluctuations should be gaussian and adiabatic (the latter because baryogenesis would occur at a later stage than inflation). But other features of the fluctuations are in principle measurable and would be a diagnostic of the specific physics. One, the ratio of the tensor and scalar amplitudes of the fluctuations, will have to await the next generation of CMB experiments, able to probe the polarization on small angular scales. Another discriminant among different theories is the extent to which the fluctuations deviate from a Harrison-Zeldovich scale-independent format ($n = 1$ in the usual notation); they could follow a different power law (i.e. be tilted), or have a ‘rollover’ so that the spectral slope is itself a function of scale. Such effects are already being constrained by WMAP data, in combination with evidence on smaller scales from present-day clustering, from the statistics of the Lyman alpha absorption-line ‘forest’ in quasar spectra, and from indirect evidence on when the first minihalos collapsed, signalling the formation of the first Population III stars that ended the cosmic dark age.

In parallel, there will be progress in ‘environmental cosmology’. The new generation of 10-metre class ground based telescopes will give more data on the universe at earlier cosmic epochs, as well as better information on gravitational lensing by dark matter. And there will be progress by theorists too. The behaviour of the dark matter, if influenced solely by gravity, can already be simulated with sufficient accuracy. Gas dynamics, including shocks and radiative cooling, can be included too (though of course the resolution isn’t adequate to model turbulence, nor the viscosity in shear layers). Spectacular recent simulations have been able to follow the formation of the first stars. But the later stages of galactic evolution, where feedback is important, cannot be modelled without parametrising such processes in a fashion guided by physical intuition and observations. Fortunately, we can expect rapid improvements, from observations in all wavebands, in our knowledge of galaxies, and the high-redshift

universe.

Via a combination of improved observations, and ever more refined simulations, we can hope to elucidate how our elaborately structured cosmos emerged from a near-homogeneous early universe.

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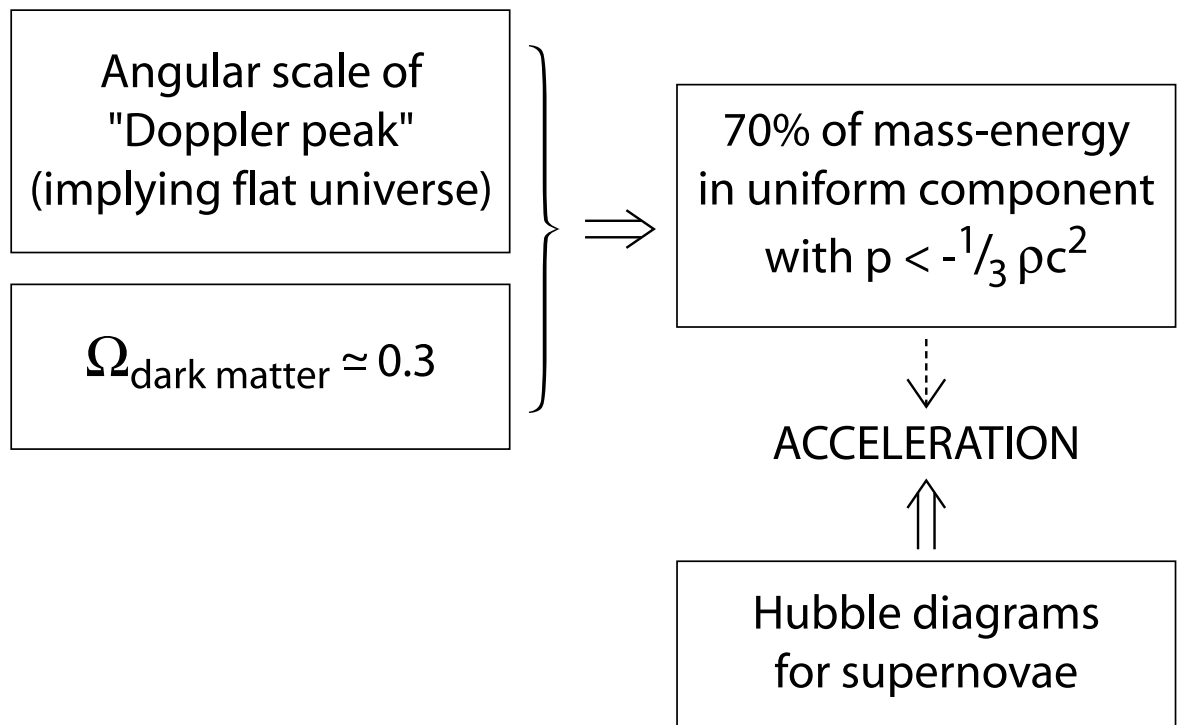


Figure 1. The network of arguments that point towards a flat Universe dominated by 'dark energy'